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FDTD Modeling of Indoor Propagation with Frequency Averaging

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***Abstract*—The presence of numerical dispersion and anisotropy in the finite-difference time-domain (FDTD) method leads to an error in the phase of the numerical waves which in turn degrades the accuracy of the simulated electric field (E-field). In this paper, the error in the mean magnitude of the numerical E-field obtained by averaging over frequency is investigated. The central frequency, at which the study is performed, is 3 GHz and different averaging bandwidths are tested to check the accuracy of representing the large-scale fading. By comparing with measurements, it is found that before averaging the maximum error in the numerical results is of 64% for empty room and 57% for office scenario. However, the maximum error in the mean magnitude of the FDTD E-field, when averaging over bandwidth of 200 MHz is employed, is of 36% and 45% for empty room and office scenario, respectively.**

***Index Terms*—Finite-difference time-domain (FDTD), numerical phase error, frequency averaging, indoor propagation.**

I. Introduction

The finite-difference time-domain (FDTD) method is one of the most widely used numerical techniques in the field of electromagnetic simulations. However, there are two effects that degrade the accuracy of this algorithm - numerical dispersion and anisotropy. In case of FDTD method, the dispersion means dependence of the numerical wave phase velocity on the frequency, cell size and time step. The numerical anisotropy, in turn, leads to directional dependence of the wave phase velocity [1], [2].

The phase error resulting from these numerical issues increases linearly with the propagation of the wave within the computational domain. In case of propagation over distances much larger than the wavelength of interest, the phase error can lead to significant decrease of the accuracy of the simulation results. A straightforward way for coping with this problem is by using finer mesh [1]. However, a disadvantage of this is that both CPU-time and memory increase which can results in inability to simulate electrically large problems. In the past years, different methods for reducing the numerical phase error has been proposed [2]–[5]. However, these numerical algorithms have some disadvantages, compared with the classical FDTD method, as complexity in the program implementation and treatment of obstacles [6].

The increasing demand for improving the quality of service of indoor wireless systems has triggered extensive investigations in the field of radiowave propagation. Due to the complicated layout of the indoor environments, simple models for characterizing the propagation might not be accurate enough for predicting the signal strength [7]. However, the progress in the computational technologies allows the use of full-wave techniques, such as the FDTD method, for simulating indoor propagation. Two-dimensional studies by using FDTD within cuts of the environment have been presented in [8]–[10], while three-dimensional characterization of the propagation has been shown in [6], [7], [11]–[13].

In most of the works related to studying indoor propagation by FDTD, a high spatial resolution has been used for the sake of reducing the numerical phase error. For the investigations in this paper, however, a coarse mesh (10 cells per free space wavelength) is employed for reducing the computational burden. The main interest of this paper is studying the inaccuracy of the mean magnitude of the numerically obtained E-field caused by numerical phase error when a low mesh density is used. For the sake of obtaining the mean results averaging over frequency is used. It should be mentioned that a comparison between mean numerical and measurement results derived by employing spatial averaging has been presented in [6], [7].

The frequency averaging in this paper is applied over different bandwidths (centered at 3 GHz) and the FDTD results are compared with measurement ones for two indoor environments. However, due to the use of such comparison for the aim of the study, it should be kept in mind that the reason for the difference between the simulation and measurement results is not only the numerical phase error. That is, even in works [7], [11], [13], where a fine mesh has been used (the numerical phase error is low), there is difference between simulation and measurement results caused by the non-perfect modeling of the studied environments. Therefore, the use of models with high spatial resolution are also not able to represent exactly the measurements.

II. Theoretical Background

The phase velocity of a numerical wave propagating in FDTD grid is a function of the wavelength, direction of propagation, cell size and time step. The dependence of the velocity on these parameters leads to presence of a phase error which increases linearly with the advance of the wave in the computational grid. In case of multipath propagation, the existence of phase error in the interfering numerical waves leads to that both magnitude and phase of the FDTD simulated resultant E-field are incorrect. This means that the numerical results for the small-scale fading are erroneous. Therefore, the large-scale characteristics, obtained by smoothing out the incorrect fast fluctuations, also contain some error.

However, in [6] the size of a cube, over which the spatial averaging is applied, needed for accurate representation of the large-scale fading regardless of the presence of a numerical phase error has been studied and it has been shown that the mean numerical E-field gets closer to the reference one by increasing the averaging stencil. In contrast to that work, in this paper the error is investigated in the mean FDTD E-field if the averaging is applied over frequency. That is, taking advantage of the wideband nature of FDTD (i.e. with one simulation large spectrum can be covered), it is studied whether by summing the simulated spectral components the errors in them (the results at each frequency are imprecise) can cancel each other to some degree and thus the mean numerical E-field to approach the reference one. The change of the error in the resultant E-field depends on the number of frequency points involved in the averaging. However, involving more frequency points in the averaging results in slower changes in the mean E-field for small displacements and thus lowering the dynamic range (lower field resolution).

Advantage of the frequency averaging over spatial one is that there is no need of knowledge of the E-field at the points around the one where the mean value is estimated. This solves the problem with the points next to the boundaries, i.e. spatial averaging over cube cannot be applied too close (the actual distance depends on the size of the stencil) to the boundary since some of the points needed for the averaging are located in the other media [6]. On the other hand, when dealing with spatial averaging the numerical anisotropy is the only source of phase error, while for frequency averaging the numerical dispersion affects the results as well, i.e. with increasing frequency (used in the averaging) the phase inaccuracy additionally increase.

III. Measurement Setup and Scenarios

For the sake of studying the accuracy of a FDTD model with low mesh density, measurements in two environments were performed: 1) large empty room; and 2) office. Commercial biconical antennas were employed for both Tx and Rx, which were connected to a network analyzer - Keysight PNA N5227A. The Rx antenna was mounted on a 3-D positioner and the measurements were conducted over a cube. The size of the cube was 14 x 14 x 14 cm^3 and each of the sides was divided into 15 points with distance between the neighbour ones of 1 cm (corresponds to $\lambda_0/10$ at 3 GHz). In total 3375 points were measured for each scenario.

Even though the main interest is on the inaccuracy of the FDTD results, because of the presence of a numerical phase error, due to comparison with measurement there is one more factor affecting the precision of the simulation results as well. The existence of this factor is caused by the imperfect modeling of the environment. The real rooms have non-smooth walls which give rise to scattered signals (apart of the specular reflection). Also, there is a lack of knowledge about the exact wall construction and the objects in the environment

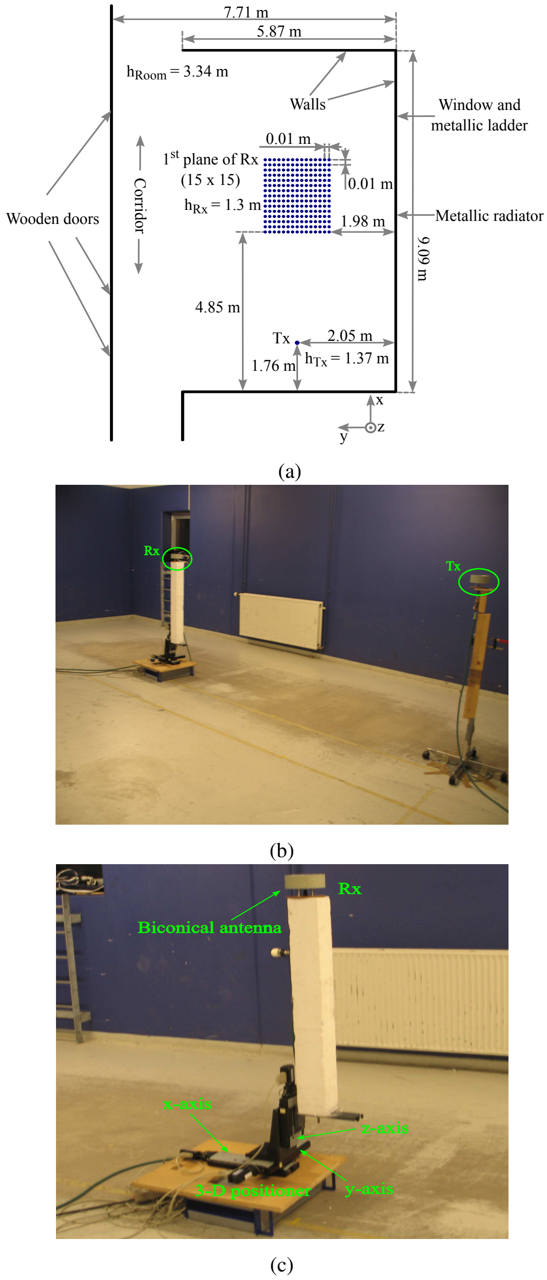


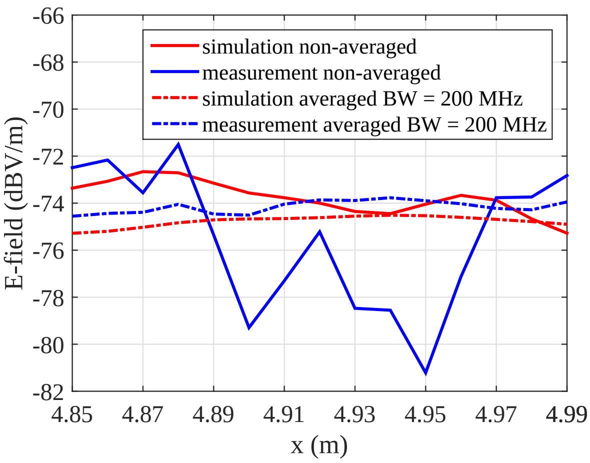
Fig. 1: (a) Layout of the empty room and location of the Tx antenna and one plane of Rx antennas (the bottom one), (b) photo of the empty room, and (c) 3-D positioner along with the Rx antenna [6].

are not perfectly modelled. It should be mentioned, that the dielectric properties of the objects within both environments were measured and used in the simulations.

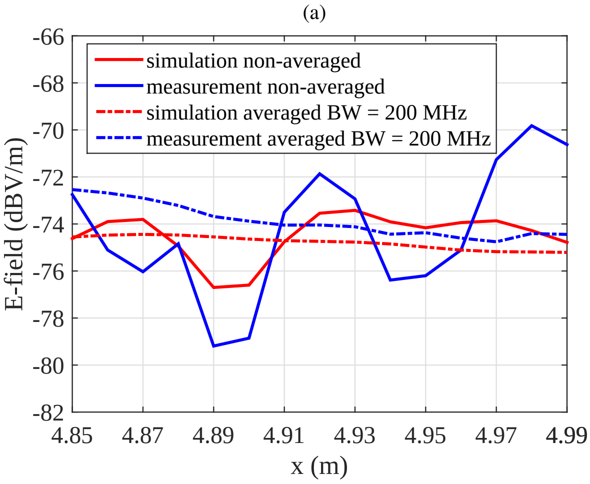
IV. Numerical Modeling

The numerical study was conducted with our in-house FDTD code. The FDTD lattice was composed of cubic cells with a size of the side of Δ = 1 cm, which corresponds to spatial resolution of $N_\lambda = \lambda_0/\Delta$ = 10 cells per wavelength at 3 GHz. The employed time step was Δt = 19.242 ps, which is the optimal one ensuring numerical stability for the selected spatial resolution.

In the numerical model, half-wavelength dipole was employed for Tx antenna and probes for Rx antennas. However, in the measurements biconical antennas at both Tx and Rx ends, showing low VSWR (below 1.2 over the studied band), were used. Due to this, the simulated results were compensated for the difference in the return loss so that to exclude the latter as a source of divergence between FDTD and measurement data.



(a)



(b)

Fig. 2: Comparison between the non-averaged and averaged ($BW = 200$ MHz) magnitude of the simulated and measured E-field for empty room scenario. The results are presented along the x-axis (the coordinate system is shown in Fig. 1(a)) and: (a) y = 2.03 m and z = 1.39 m, and (b) y = 2.07 m and z = 1.4 m.

V. Simulation and Measurement Results

A. Empty Room

The empty room, where the measurement was conducted, had size of 9.09 x 7.71 x 3.34 m^3. The floor plan is shown in Fig. 1(a), photo of the room in Fig. 1(b), and closed view to the positioner with the placed Rx antenna in Fig. 1(c). In the rest of the paper, BW is used for designating the bandwidth over which the averaging is applied (if no averaging then $BW = 0$). The distance between the frequency points involved in the averaging is 2 MHz.

The results for non-averaged and averaged (over $BW = 200$ MHz being the largest studied averaging bandwidth) are shown in Fig. 2. Large difference between the non-averaged numerical and measurement results can be observed. However, the agreement between the mean results is much better.

The error in the numerical results at point with coordinates (x, y, z) is defined as:

$$\Delta E(x,y,z) = \frac{||E^{meas}_{nav(av)}(x,y,z)| - |E^{sim}_{nav(av)}(x,y,z)||}{max(|E^{meas}_{nav(av)}|)} \tag{1}$$

where $|E^{meas}_{nav(av)}|$ is the measured non-averaged (averaged) magnitude of the E-field; $|E^{sim}_{nav(av)}|$ is the simulated non-averaged (averaged) magnitude of the E-field; $max(|E^{meas}_{nav(av)}|)$ is the maximum measured non-averaged (averaged) magnitude of the E-field. The value of these parameters changes with BW.

The results for the maximum error (ΔE_{max}) are presented in Table I. As one can see the largest error is observed in the non-averaging case. However, ΔE_{max} decreases with increasing the averaging bandwidth, being of 36% for $BW = 200$ MHz. That is, the larger averaging bandwidth lowers the effect of the numerical phase error and the other sources of error (due to the imperfect modeling) on the large-scale results but also lowers the field resolution.

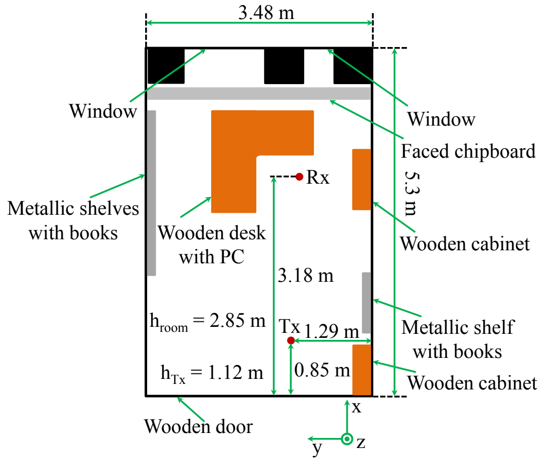
The maximum error, however, points out only the highest discrepancy between the simulation and measurement results and it is possible that large mismatch appears only in a small number of points. Due to this, it is worthy to investigate some other parameter as 95th percentile of the error. The results in Table I show that this parameter decreases with increasing the bandwidth used for averaging and for $BW = 200$ MHz it is 23%. As can be observed from the data, the percentile is significantly lower than ΔE_{max} meaning that most of the errors are much below the maximum one.

Averaging bandwidth - BW (MHz)	0	20	52	100	152	200
ΔE_{max} (%)	64	56	50	43	37	36
95th percentile (%)	40	37	33	26	24	23

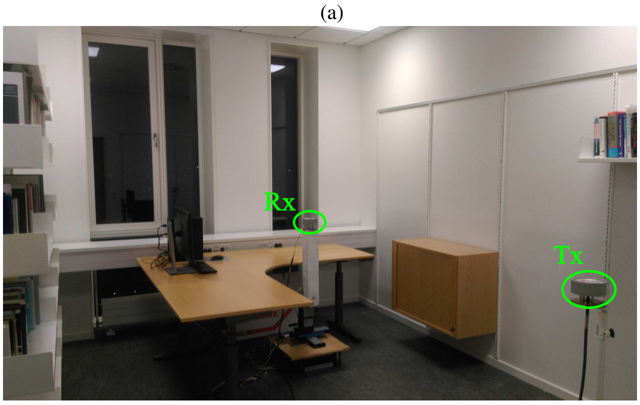
TABLE I: Maximum error ΔE_{max} and 95th percentile of the error in the magnitude of the simulated E-field versus the averaging bandwidth BW for empty room scenario.

B. Office

In order to study the accuracy of the averaged results in more realistic scenario, measurements in an office environment were performed. The size of the office was 3.48 x 5.3 x 2.78 m^3, with layout shown in Fig. 3(a) and photo of it in Fig. 3(b). It should be mentioned, that only the central position of the Rx antenna in the cube is given in Fig. (a) and it has the same coordinates along y- and z-axes as the Tx antenna.

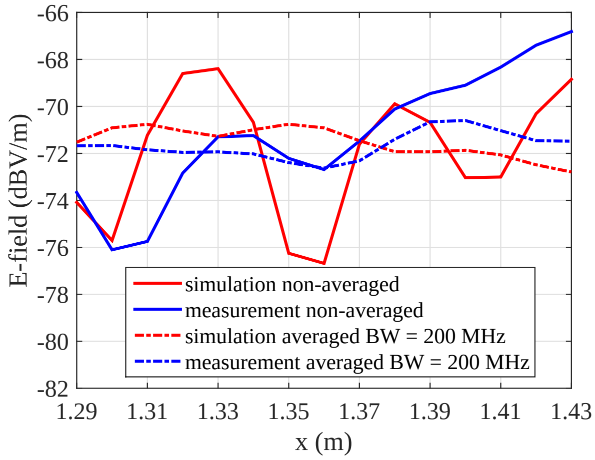


(a)

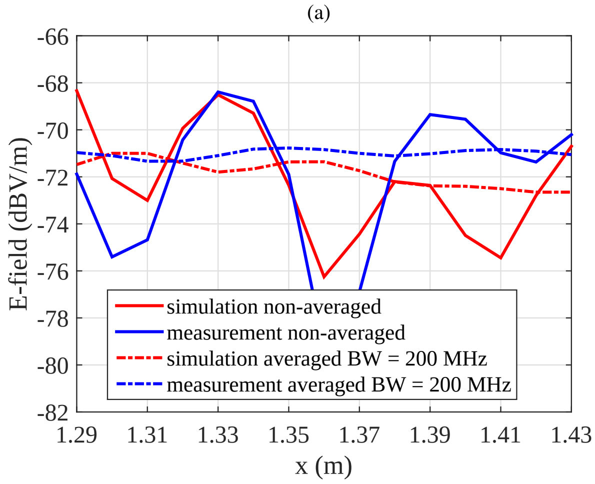


(b)

Fig. 3: (a) Layout of the office and location of the Tx antenna and Rx antenna (only the very central position of the Rx antenna in the cube is shown, having the same y- and z-components as the Tx antenna), and (b) photo of the office [6].



(a)



(b)

Fig. 4: Comparison between the non-averaged and averaged (BW = 200 MHz) magnitude of the simulated and measured E-field for office scenario. The results are presented along the x-axis (the coordinate system is shown in Fig. 3(a)) and: (a) y = 1.27 m and z = 1.14 m, and (b) y = 1.29 m and z = 1.29 m.

Comparison between simulation and measurement results (before and after averaging over BW = 200 MHz) is presented in Fig. 4. As in the case of empty room, there is a pronounced discrepancy between the non-averaged magnitude of the simulated and measured E-field. However, smaller difference between the averaged numerical and measured magnitude of the E-field is observed.

Table II shows the results for the maximum error and 95th percentile of the error. As can be expected, the largest divergence of the numerical results is observed before averaging. The simulated data represents closer the measurement one with increasing the bandwidth over which the averaging is applied. Frequency averaging with BW = 200 MHz shows ΔE_{max} of 45% and 95th percentile of 27%.

Comparing the results in Table I and II, it can be seen that ΔE_{max} before averaging is lower in case of office environment even though it is more cluttered (the model is less precise) and there are stronger multipath (more waves summing with inaccurate phases because of the numerical error). Hereof, one would expect the opposite, i.e. the error in this environment to be higher than the one in the empty room. Indeed, that is the case - the absolute difference $||E_{nav}^{meas}| - |E_{nav}^{sim}||$ for the empty room is lower than that for the office. However, the distance Tx-Rx is larger for empty room and therefore the maximum magnitude of the measured non-averaged E-field is lower. For small averaging bandwidths the difference between the two scenarios in terms of ΔE_{max} and 95th percentile is not so significant. However, for $BW > 50$ MHz the numerical results for the empty room environment are closer to the measurement ones. Making a comparison with spatial averaging in [6] - for the empty room scenario spatial averaging over a cube with side length of 5 cm (5 cells) provides ΔE_{max} between that obtained from frequency averaging with $BW = 52$ MHz and $BW = 100$ MHz and 95th percentile between that for $BW = 20$ MHz and $BW = 52$ MHz. For the office scenario, spatial averaging with the same stencil leads to ΔE_{max} similar to that determined for $BW = 152$ MHz and 95th percentile same as that for $BW = 100$ MHz.

Averaging bandwidth - BW (MHz)	0	20	52	100	152	200
ΔE_{max} (%)	57	56	55	53	48	45
95th percentile (%)	42	38	34	32	31	27

TABLE II: Maximum error ΔE_{max} and 95th percentile of the error in the magnitude of the simulated E-field versus the averaging bandwidth BW for office scenario.

VI. Conclusion

The accuracy of the frequency averaged magnitude of the FDTD simulated E-field has been studied in this paper. A low mesh density of only 10 cells per free space wavelength (at 3 GHz being the central frequency of the study) has been used in the numerical models in order to decrease the computational burden. Such a spatial resolution on the other hand leads to a higher numerical phase error. For the sake of investigating the error in the numerical results, measured E-field is used as a reference one. It has been found that there is a significant discrepancy between the non-averaged FDTD and measured magnitude of the E-field. However, the error in the frequency averaged numerical results is lower and also decreases with increasing the bandwidth over which the averaging is applied. In general, even FDTD model with a low spatial resolution can represent accurately the large-scale characteristics of the channel if averaging over a broad enough frequency band is employed.

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